
High-Impedance and Low-Impedance Fault Protection Requirements and Verification Testing for Electric Aircraft Power Systems

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Overview



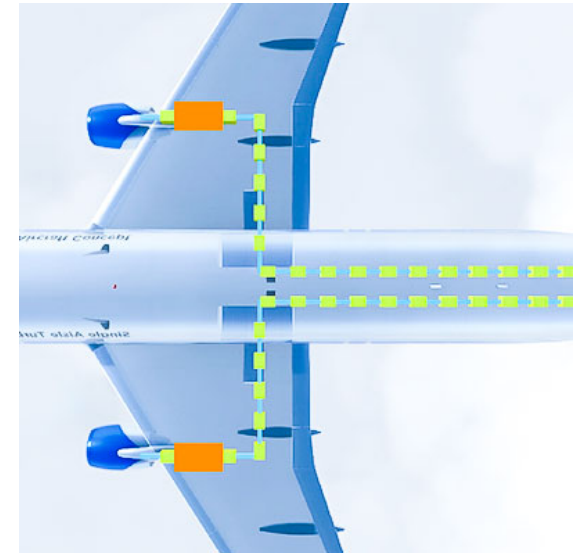
- Background
 - Power quality investigations
- DC Fault Injection
 - High-Impedance Faults
 - Low-Impedance Faults
- Fault Injection Unit Design/Capability
 - High-Impedance Fault Injection
 - Low-Impedance Fault Injection
- Power Quality Fault Testing
 - Testbed multistring configuration
 - Fault Testing in Power Quality Testbed
- Conclusion



Power Quality Investigations



- High voltage direct current (HVDC) 1 kV power quality (PQ) investigations
 - Enable benefits of electric aircraft propulsion
 - Feeding results to international standards
- New test methods are required for HVDC systems
- Prompted development of the DC Fault Injection Unit
 - Multi-purpose, rack-mount unit for HVDC propulsion system fault testing



DC Fault Injection Unit

- DC Fault Injection Unit (FIU) capable of injecting faults and large signal disturbances onto a HVDC bus
 - Designed and built to test electrical power system (EPS) power quality in abnormal and faulted conditions
 - Advantages:
 - High configurability
 - High adaptability
 - Lower cost and smaller footprint than similar EPS equipment
- High-impedance faults
 - Abnormal condition of fault current that may be challenging to detect and clear
 - Ability of EPS to remove these faults within a specified timeframe to prevent system damage must be verified by repeatable test methods
- Low-impedance faults
 - Excessively high currents
 - Fault clearing and protection coordination must be verified by repeatable test methods



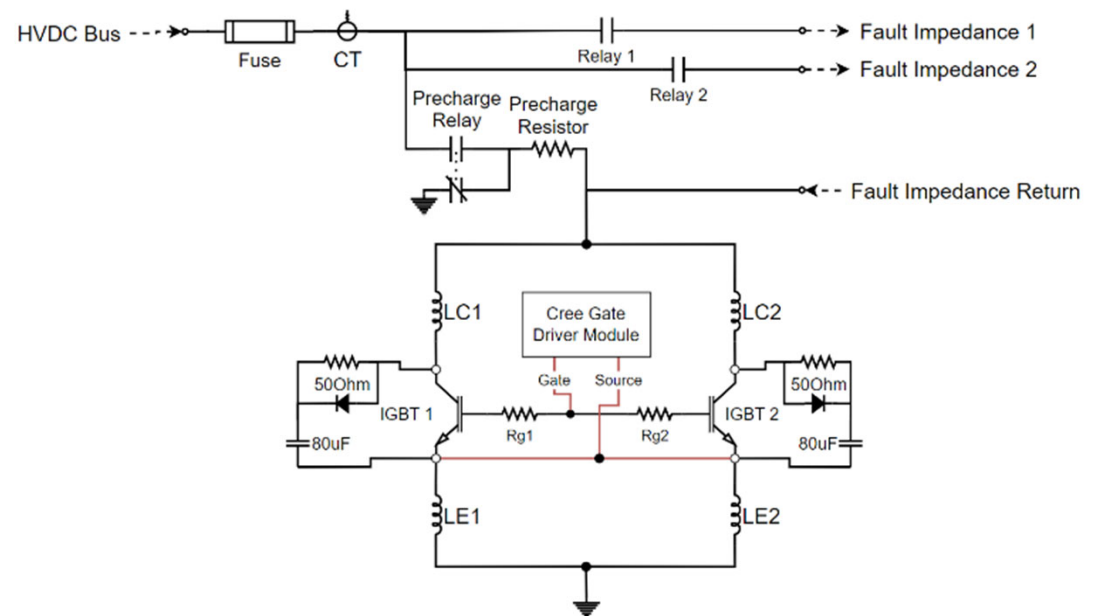
DC Fault Injection Unit

DC Fault Injection Unit Design/Capability

High Impedance Fault Injection Unit



- High-Impedance Faults
 - Parallel high power Silicon Carbide (SiC) Insulated Gate Bipolar Transistors (IGBTs)
 - Maximum 1kA soft fault emulation
 - Maximum 1kV anode-cathode
 - Selectable fault impedance (HV contactors)
 - Protective components
 - Custom RC snubber PCB
 - DC photovoltaic fuse



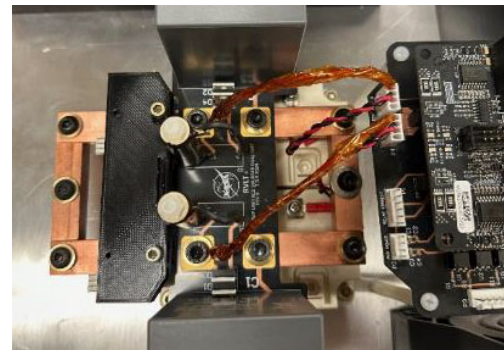
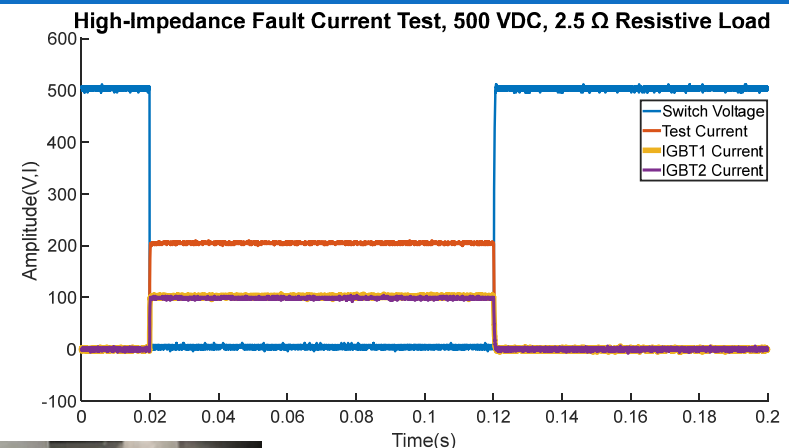
High-Impedance Fault Injection Circuit

DC Fault Injection Unit Design/Capability

High Impedance Fault Injection Unit (cont.)



- Parallel balanced current sharing
 - Parallel SiC IGBTs introduce current balancing challenge
 - Central gate driver ensures simultaneous switch commutation
 - Minimized branch inductance variance
 - Tight branch connections ensure balanced current sharing during injection interval
- Minimized overall inductance
 - Tightly positioned switches



IGBT Connection and Spacing

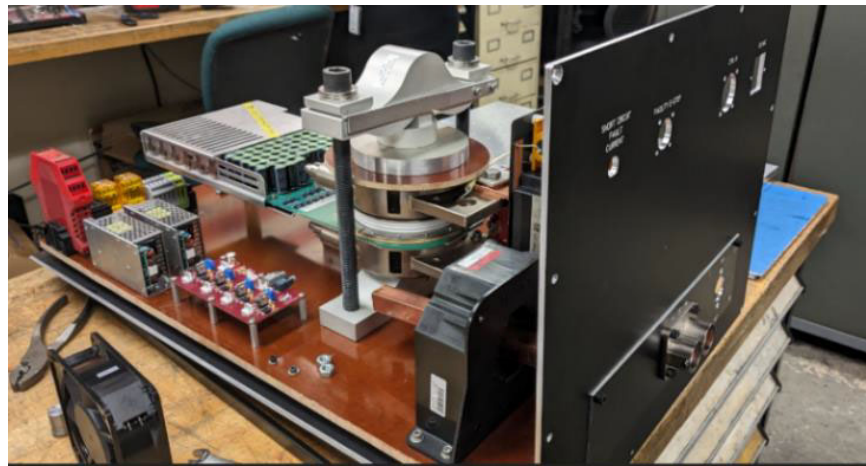
Parallel IGBT Fault Current Test

DC Fault Injection Unit Design/Capability

Low Impedance Fault Injection Unit



- Low-Impedance Fault Injection Unit
 - Integrated Gate-Commutated Thyristor (IGCT) generates hard fault and interrupts it (should switchgear fail to do so)
 - Maximum 6kA (derated to 4kA)
 - Maximum 4.5kV anode-cathode
 - Fiber optic ports
 - Control signal switches gate unit on and off
 - Feedback gives switch status
 - Protective components
 - Handmade di/dt-limiting air-core inductor
 - Custom RC snubber PCB
 - Metal oxide varistor (MOV)



Low-Impedance Fault Injection Unit Test Enclosure

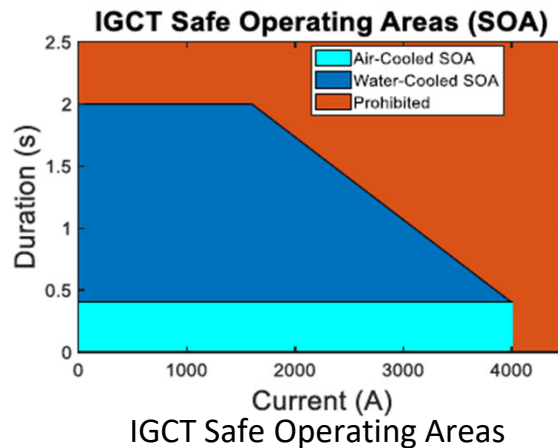
DC Fault Injection Unit Design/Capability

Low Impedance Fault Injection Unit (cont.)

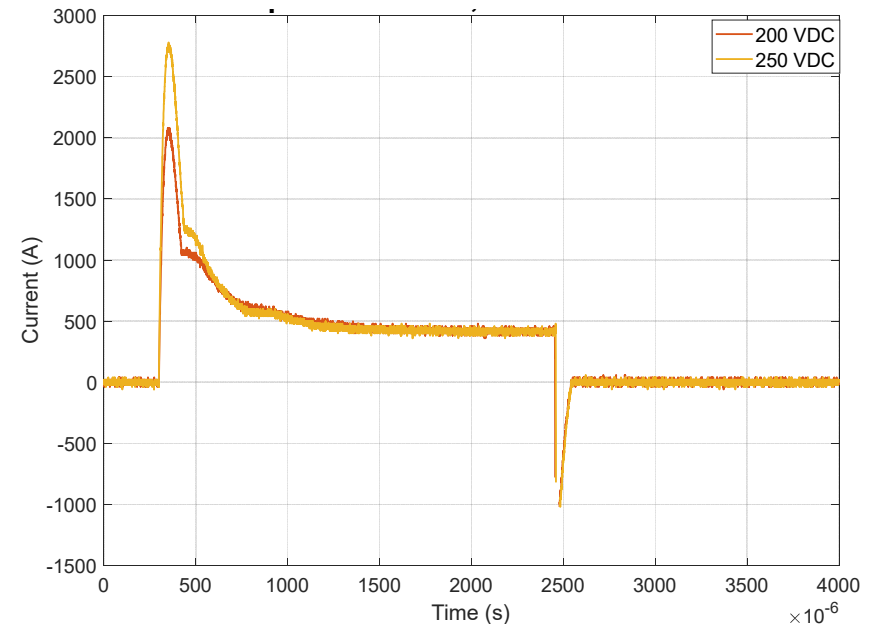


➤ Low-Impedance Faults

- Thermal analysis defined IGCT safe operating area (SOA)
 - Water-cooled or air-cooled test conditions
 - 80 W heat dissipation
- Testing conducted with 0.1 Ω , 250 W wire-wound chassis-mount resistor load
 - Source voltage up to 250 VDC
 - Power supply current-limited at 500 A
 - Pulse durations limited to 400 ms (air-cooled only bench testing)



**IGCT Line Currents at 200 V and 250 V Source Voltage,
0.1 Ω Resistive Load, 2 ms Switch Closed Time**



Low-Impedance Fault Injection Test Data

DC Fault Injection Unit Design/Capability



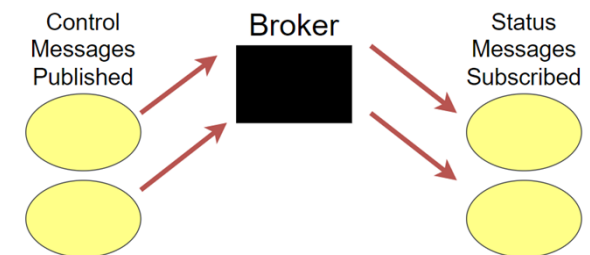
- Enclosure control and interface
 - Single-board computer operates each test unit through Internet of Things (IoT) Message Queuing Telemetry Transport (MQTT) GUI
 - Simple machine-to-machine telemetry
 - Operates switches and relays in each unit
 - Separate GUI pages to control each FIU enclosure
 - Python client monitors messages published from GUI and enclosure feedback to determine control states

The screenshot shows the 'FIU High-Impedance Fault Test Controller' interface. It has a dark blue background with white text. At the top is a button labeled 'FIU HOME PAGE'. Below it is a section titled 'IMPEDANCE SELECTION' with two buttons: 'LOAD 1' and 'LOAD 2'. The next section is 'IGCT CONTROLS' with a button 'GATE DRIVER PWR ENABLE'. The bottom section is 'FAULT SECTION', which includes a 'Time Duration (milliseconds)' input field with a slider, a 'SUBMIT' button, a red-outlined 'SEND FAULT' button, and a yellow-outlined 'RESET' button.

High-Impedance FIU GUI

The screenshot shows the 'FIU Short Circuit Test Controller' interface. It has a dark blue background with white text. At the top is a button labeled 'FIU HOME PAGE'. Below it is a section titled 'IGCT CONTROLS' with a button 'IGCT ENABLE'. The bottom section is 'FAULT SECTION', which includes a 'Time Duration (milliseconds)' input field with a slider, a 'SUBMIT' button, and a red-outlined 'SEND FAULT' button.

Low-Impedance FIU GUI



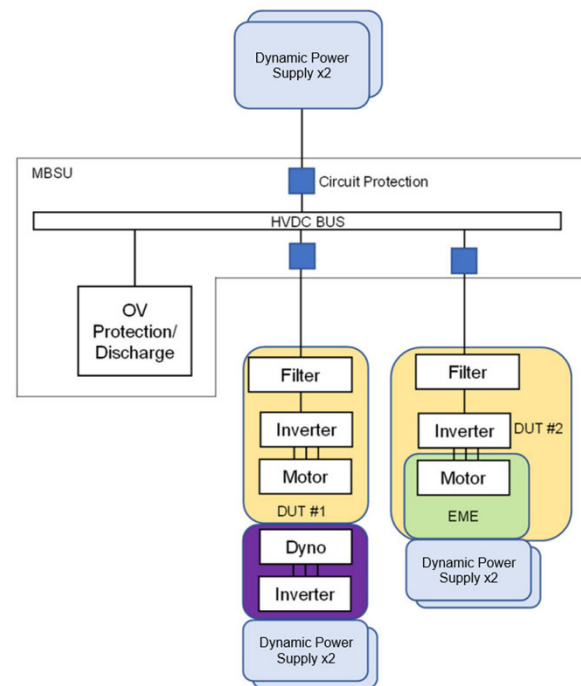
MQTT – Publish Subscribe Model

DC Fault Injection Unit Design/Capability

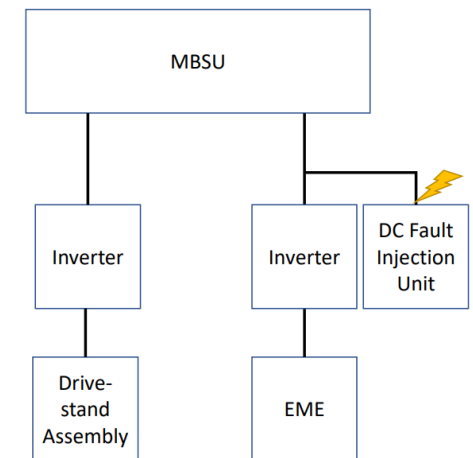


➤ Fault Testing in Revolutionary Vertical Lift Technology Testbed

- Advanced Reconfigurable Electrified Aircraft Laboratory (AREAL)
 - 200kW, 300VDC-1kVDC (peak)
 - COTS inverter/motor pair or inverter/electric motor emulator
 - Power Quality Testing
- Multistring configuration
 - Parallel motor (or emulated motor) loads fed by dynamic high-voltage sources
 - Main Bus Switching Unit (MBSU) houses protection elements for loads and cables connected to bus
 - Pass/fail criteria will be used to determine whether EPS and loads connected to the bus can withstand faulted operation



AREAL System Configuration



AREAL Fault Injection Configuration

Conclusion and Future Work



- Fault injection apparatuses were built and integrated into a single DC Fault Injection Unit
 - Parallel IGBTs generated high-impedance faults
 - IGCT generated low-impedance faults
- Results obtained from each unit will enable characterization and testing of high-voltage DC EPS for power quality when integrated into AREAL
- Enclosures enable validation of proposed power quality specifications
- Future work
 - Modify AREAL for multistring operation
 - Integrate unit into AREAL multistring configuration
 - Carry out multistring off-nominal operation

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